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SEPTEMBER 1977

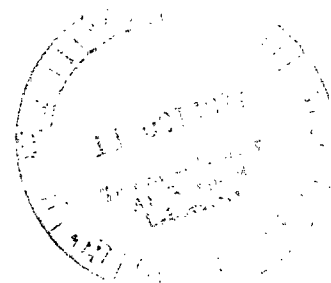
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# Effect of Carbon Content on Friction and Wear of Cast Irons

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National Aeronautics  
and Space Administration

**Scientific and Technical  
Information Office**

1977

# EFFECT OF CARBON CONTENT ON FRICTION AND WEAR OF CAST IRONS

by Donald H. Buckley

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## SUMMARY

An investigation was conducted to determine the effect of carbon content on the friction and wear of cast irons and wrought steels. The cast irons examined were both gray and white cast irons. Repetitive reciprocal sliding friction experiments were conducted on flats of the experimental alloys. A 52100 steel ball rubbed the surfaces under a load of from 25 to 250 grams and at a sliding velocity of 5 centimeters per minute. The experiments were conducted in an argon atmosphere at a temperature of 23° C.

The results of the study indicate that gray cast iron has lower friction and wear characteristics than does white cast iron. Further, with increases in carbon content, wear is more markedly reduced than it is with white cast iron. Wear of gray cast iron is linearly related to load and friction coefficient is affected by relative humidity with a minimum in friction existing at about 50 percent relative humidity. There does not appear to be a relationship between hardness and the wear characteristics of these ferrous alloys.

## INTRODUCTION

Cast irons, because of their good resistance to wear, have been used in a wide variety of mechanical systems for many years. They have been used in piston rings, bearings, brakes, seals, and so forth.

The wear resistance of cast irons depends very heavily on the elements and structures present. The influence of alloying elements on wear behavior of cast irons was recognized very early (ref. 1). Disagreement, however, has existed as to the specific role of certain elements in affording wear resistance (ref. 2).

In general, it is thought that wear decreases with increased pearlite and graphite content (ref. 3). Further, those elements which tend to increase hardness of the cast iron will increase resistance to wear (ref. 4).

The objective of the present investigation was to examine, in a systematic manner, the role of the element carbon on the reciprocal dry sliding friction and wear behavior

of both white and gray cast irons. Subsequent studies will deal with the effect of other alloying elements on wear while holding the carbon content constant. Friction and wear experiments were conducted with a 52100 steel ball sliding, in reciprocating motion, on cast iron surfaces at a sliding velocity of 5 centimeters per minute, loads of from 50 to 250 grams, room temperature, and in an argon atmosphere.

## MATERIALS

The white cast iron, gray cast iron, and the reference steels used in this investigation were prepared by a metallurgical services laboratory primarily as teaching aids in the demonstration of various structures. The elemental composition of these materials in weight percent is presented in table I. The ball specimen was of 52100 bearing steel and was a standard bearing ball. Both specimen surfaces had a 1 to 2 rms surface finish.

## APPARATUS

The apparatus used in this investigation is shown schematically in figure 1. It consisted essentially of the specimens, a 2.5-millimeter-diameter SAE 52100 steel ball, and a flat of the cast irons or steels 25.4 millimeters in diameter. The flat specimens were mounted in a vice on a miniature table which was driven back and forth by a mechanical drive system containing a gear box, a set of bevel gears, and a lead screw driven by an electric motor. Total distance of travel was 15.0 millimeters in one direction. Microswitches located at each end of the traverse reversed the direction of travel so that the steel ball retraced the original track from the opposite direction. This process was continuously repeated for a duration of 1 hour.

The steel ball was loaded against the flat disk with dead weights. The arm retaining the steel ball contained strain gages which continuously monitored the friction force.

The arm containing the steel ball could be moved normal to the direction of the wear tracks. Thus, multiple tracks could be generated on a single surface.

A variable speed gear box was attached to a small electric motor for controlling sliding velocity. Loads also could be varied from 0 to 250 grams. The entire apparatus was housed in a plastic box. The atmosphere in the box could be closely controlled.

## EXPERIMENTAL PROCEDURE

The steel ball and flat specimens were cleaned with levigated alumina rinsed with

distilled water and then with 200-proof ethyl alcohol. Surfaces were dried with dry nitrogen gas. The specimens were then mounted in the apparatus.

Load was applied to the steel ball. The cover of the plastic box was closed and the entire system purged with a positive pressure of argon gas for a period of 15 minutes prior to the initiation of sliding.

After completion of the purge, sliding was initiated and continued for a period of 1 hour. Friction force was continuously recorded for the 1-hour period. The wear scar width on the flats of cast iron and steel was measured upon completion of the experiment.

## RESULTS AND DISCUSSION

### Gray Cast Iron

Photographs of the microstructure of the gray cast irons are presented in figures 2 and 3. In figure 2(a) for 2.12 percent carbon, thin graphite flakes are sparsely distributed in a pearlitic matrix. In figure 2(b) for 3.02 percent carbon, there is a greater amount of graphite in a pearlitic matrix and the flakes are coarser. The amount of graphite is still greater in figure 2(c) with 3.66 percent carbon and is greatest in figure 2(d) with 4.32 percent carbon.

Figure 3 is an enlargement of the gray cast iron microstructure containing 4.32 percent carbon. It indicates the pearlitic matrix with free graphite.

Friction and wear experiments were conducted in argon with the gray cast iron microstructural compositions presented in figures 2 and 3. The results obtained are presented in figure 4. Both friction and wear were reduced with increasing carbon content of the gray cast iron. A 2-percent increase in carbon content resulted in a fourfold decrease in friction coefficient. Further, a linear reduction in wear track width occurred with increasing carbon content. Surface profilometer examinations of the wear tracks indicated that wear occurred to the cast iron. The wear profile depth was not hemispherical as might be observed when the flat undergoes plastic deformation but generally equidistant in depth from the surface along the width of the track.

The load applied to the steel ball to obtain the results of figure 4 was 50 grams. In order to determine the effect of load on friction and wear, experiments were conducted at various loads of from 50 to 250 grams for a gray cast iron having 4.32 percent carbon. The results obtained are presented in figure 5.

In figure 5, the friction coefficient decreases with increasing load to 150 grams and then remains unchanged with further increases in load. Considering that sliding was conducted under dry, unlubricated conditions, the friction is extremely low at the higher loads, 0.15.

The wear of the gray cast iron is a direct linear function of the track width. The greater the load, the greater is the wear.

Figure 6 is a photomicrograph of the wear scar on the 3.02 percent gray cast iron structure. The graphite flakes have been smeared out over the surface as a result of the rubbing process. In reference 5, the observation was made that wear to cast iron was affected by the size and distribution of graphite flakes. In the present study, wear was found to be related to total carbon content and the greater the carbon content the greater was the fraction of contact surface area covered by smeared graphite. This would seem to indicate that a relationship exists between graphite content and wear for cast iron.

In an ordinary air environment, the surface layers on the surface of cast iron have been found to be a mixture of graphite and iron oxide,  $\text{Fe}_3\text{O}_4$  (ref. 6). With the argon environment used herein, the surface present in the wear track of figure 6 must be considered to be essentially graphite with a minimal amount of normal residual surface oxide.

The results obtained in figures 4, 5, and 6 were for flake graphite in gray cast iron. Studies have been conducted on spheroidal graphite in cast iron (ref. 7). While the author of reference 7 did not specifically examine the effect of carbon content on friction and wear, he did conclude that the wear characteristics of spheroidal graphite and flake graphite cast irons were similar. It might, therefore, be reasonable to assume that carbon content in spheroidal graphite in cast iron may have a similar effect on friction and wear as that observed for a gray cast iron herein.

The conclusion that graphite in gray cast iron is lubricating can be strengthened if the surface of the gray cast iron can be shown to be sensitive to moisture. Since the graphite in gray cast iron is lubricating the surface, then the friction behavior of that surface should be sensitive to moisture. This must be so because the friction behavior of graphite, as is well known, is very sensitive to moisture.

Friction and wear experiments were conducted with 4.32 percent carbon in gray cast iron in an argon environment containing various percentages of relative humidity from zero to operating also under water.

The results obtained in these varying humidity experiments are presented in figure 7. An examination of the friction data of figure 7 indicates that the friction coefficient of gray cast iron is sensitive to moisture. Friction coefficient decreases with increasing relative humidity to 50 percent and then increases thereafter. The decrease with increase in relative humidity to 50 percent is consistent with the friction behavior of graphite.

At 80 percent relative humidity and under water, the wear surface contained iron oxide ( $\text{Fe}_2\text{O}_3$ ) identified from its characteristic color in addition to graphite. The presence of this oxide was not observed in the wear track at 50 percent relative humidity and less. Iron oxide ( $\text{Fe}_2\text{O}_3$ ) is abrasive and therefore may account for the increase in

friction observed at the higher amounts of humidity. It can also explain the increase in wear observed in water.

The graphite flakes present in the gray cast iron take a period of time to become smeared out over the surface when sliding or rubbing is initiated on a virgin surface. As a consequence, friction is initially high and decreases with time as indicated in the dry sliding data of figure 8. After some period of time, an equilibrium condition is reached where the surface is fairly uniformly covered with graphite and friction reaches a constant value of 0.2.

If the decrease in friction coefficient with increase in relative humidity in figure 7 is related to a sensitivity of the graphite rather than the iron surface to moisture, then a decrease in friction with sliding time should be observed similar to that seen in dry sliding. Iron, itself, does not exhibit this time dependent sensitivity. The results presented in figure 8 for a 50-percent relative humidity indicate that there is a time dependent sensitivity. Thus, it is the graphite sensitivity to moisture which affects the friction behavior of gray cast iron.

Oils will readily chemisorb to metal surfaces while the bonding of graphite to metal is poor. It is possible therefore that the graphite film on the surface of gray cast iron might be readily displaced by a lubricating oil. Friction and wear experiments were therefore conducted with gray cast iron in the presence of oil. The results of these tests showed that, even when gray cast iron is lubricated with a mineral oil, graphite smears out in the wear contact zone as indicated in the photomicrograph of figure 9. The amount of graphite is less and the film is thinner but is nonetheless present.

#### White Cast Iron

The carbon content of white cast iron like that of gray cast iron can vary and therefore also possibly influence friction and wear. Figure 10 contains photomicrographs of white cast iron structures containing various amounts of carbon from 3.00 to 4.32 percent.

In figure 10(a) with 3.00 percent carbon, pearlite is present in a dendritic formation together with a ledeburite eutectic. There are approximately equal quantities of pearlite and ledeburite. The specimen in figure 10(b) with 3.54 percent carbon is similar to that of 10(a) but there is less pearlite corresponding to the greater carbon content. Figure 10(c) containing 4.18 percent carbon consists nearly wholly of ledeburite eutectic. There are some small islands of pearlite. The structure of figure 10(d) with 4.32 percent carbon consists of iron carbide needles in well-formed ledeburite. Some graphite also appears in this structure.

Friction, wear, and hardness measurements were made with the structures shown in figure 10. The data obtained as a result of these experiments are presented in figure 11. Hardness increases with the increase in carbon content to 4.18 percent carbon. Then, at 4.32 percent, there is a slight decrease in hardness.

The wear to the white cast iron continuously decreases with increasing carbon content. This behavior is analogous to that observed with gray cast iron.

The coefficient of friction for the white cast iron in figure 11 increases to 4.18 percent carbon and then at 4.32 percent carbon decreases noticeably. With the gray cast iron increasing the carbon content resulted in an increased graphite content and a corresponding decrease in friction. In figure 11, the amount of pearlite decreases as that of ledeburite increases. It is only at the 4.32 percent carbon composition that graphite appears and the friction decreases.

A comparison is made for the hardness and wear differences of gray and white cast iron in figure 12. It is of interest to note over the same range of carbon content that while the white cast iron is considerably harder than the gray cast iron the wear is less for the gray cast iron. Further, the slope of the curve for the change in wear with carbon content is significantly steeper for gray than it is for white cast iron. Thus, from considerations of wear, gray cast iron is superior to white cast iron and increases in carbon content produce a more drastic reduction in wear with gray cast iron than with white cast iron. In addition, there does not seem to be a relationship between wear resistance and hardness for cast irons. The softer cast iron (gray) afforded the greatest resistance to wear. It appears that with respect to friction and wear the form of the carbon in ferrous alloys is as important as the content.

### Wrought Steels

Because of the obvious importance of carbon content in the friction and wear behavior of cast irons, similar experiments were conducted with wrought steels. All alloying elements except carbon were held fairly constant. The composition of the steels examined is presented in table I. The carbon content varies from approximately 0.1 percent to 1.3 percent.

Friction and wear data for the wrought steels containing various amounts of carbon are presented in figure 13. Over the entire carbon composition range examined, the coefficient of friction remained at the same approximate value of 0.95. The wear, like friction, is independent of carbon content to 0.85 percent carbon. At 0.85 percent carbon, a decrease in wear is observed. These results are contrary to what was anticipated. Because of the wear patterns of the cast irons, and work with other alloying elements in ferrous alloys where increases in concentration of certain alloying elements results in outward wear, it was believed that wear would decrease with increasing



carbon content.

The hardness of the steel increased with increasing carbon content as might be anticipated. The data indicating this effect are presented in figure 14. Again, it is obvious that a relationship does not exist with hardness and wear for the wrought steel. The mating 52100 steel ball underwent very little wear. Wear was relatively constant to 0.8 percent carbon in figure 13 while hardness continued to increase to that composition.

## CONCLUSIONS

Based upon the reciprocating friction and wear results obtained in this investigation with various amounts of carbon in cast irons and wrought steel, the conclusions are drawn as follows:

1. Gray cast irons have lower friction and wear characteristics than do white cast irons.
2. Increases in carbon content in gray cast irons produce more marked reductions in wear than do the same carbon increases in white cast iron.
3. A linear wear track width relationship with load exists with gray cast iron.
4. The friction behavior of gray cast iron is sensitive to humidity. There exists an optimum for minimum in friction at 50 percent relative humidity.
5. The changes in the friction and wear behavior of cast irons and wrought steels with increased carbon content do not appear to be related to hardness.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, July 1, 1977,  
506-16.

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TABLE I - COMPOSITION OF GRAY  
CAST IRON, WHITE CAST IRON,  
AND WROUGHT STEEL

Composition, wt %					
C	Si	Mn	S	P	Cr
Gray cast iron					
2.12	2.04	0.52	0.027	0.018	----
3.02	2.07	.50	.030	.014	----
3.66	2.10	.52	.025	.024	----
4.32	2.04	.52	.032	.024	----
White cast iron					
3.00	0.48	0.48	0.021	0.012	0.95
3.54	.42	.50	.024	.012	1.00
4.18	.41	.50	.030	.019	.98
4.32	.44	.52	.023	.006	1.05
Wrought steel					
0.11	0.21	0.85	0.02	0.021	----
.23	.22	.85	.035	.024	----
.31	.22	.84	.038	.030	----
.40	.12	.68	.034	.025	----
.68	.33	.84	.045	.038	----
.80	.22	.21	.010	.020	----
1.31	.25	.35	.007	.010	----

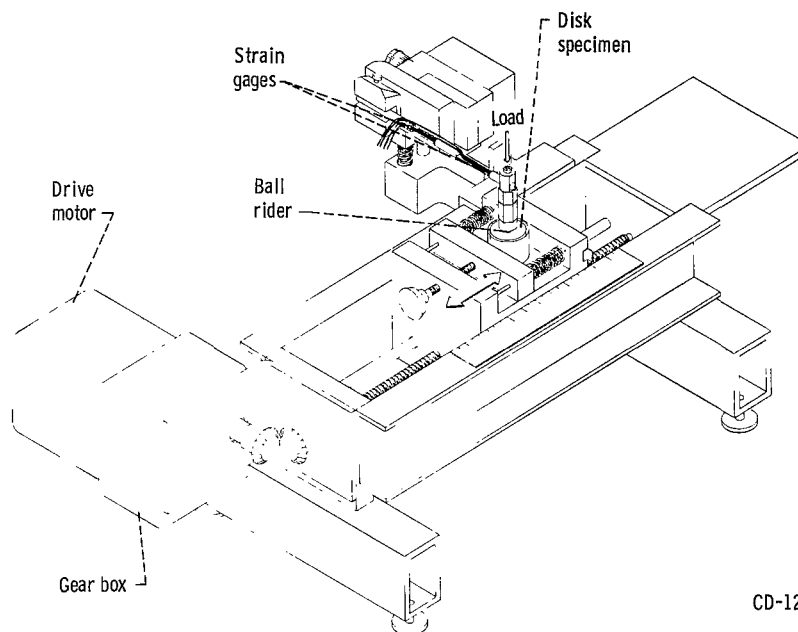
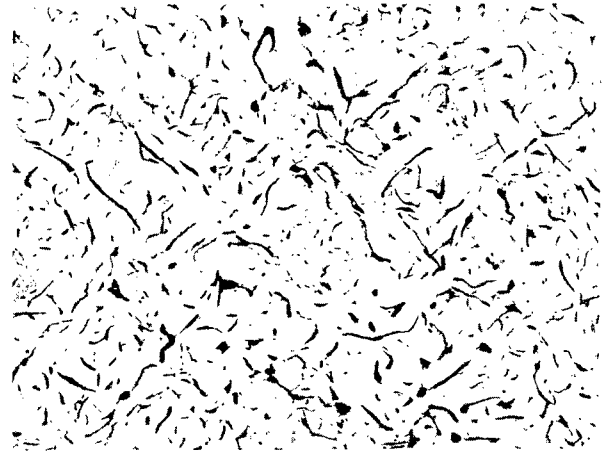


Figure 1. - Friction and wear apparatus.

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(a) 2.12 percent carbon.



(b) 3.02 percent carbon.



(c) 3.66 percent carbon.



(d) 4.32 percent carbon.

Figure 2. - Photographs of gray cast iron microstructure.

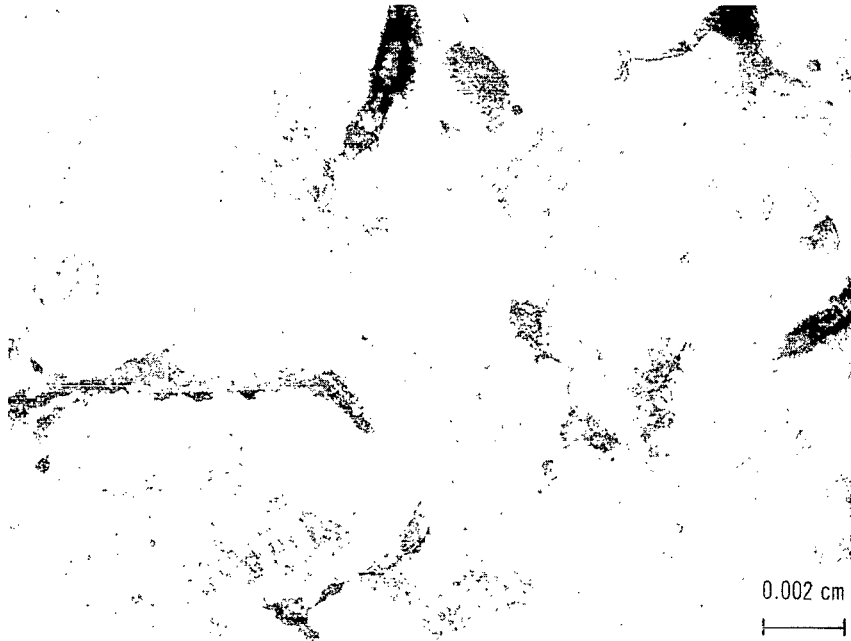


Figure 3. - Pearlitic structure in gray cast irons.

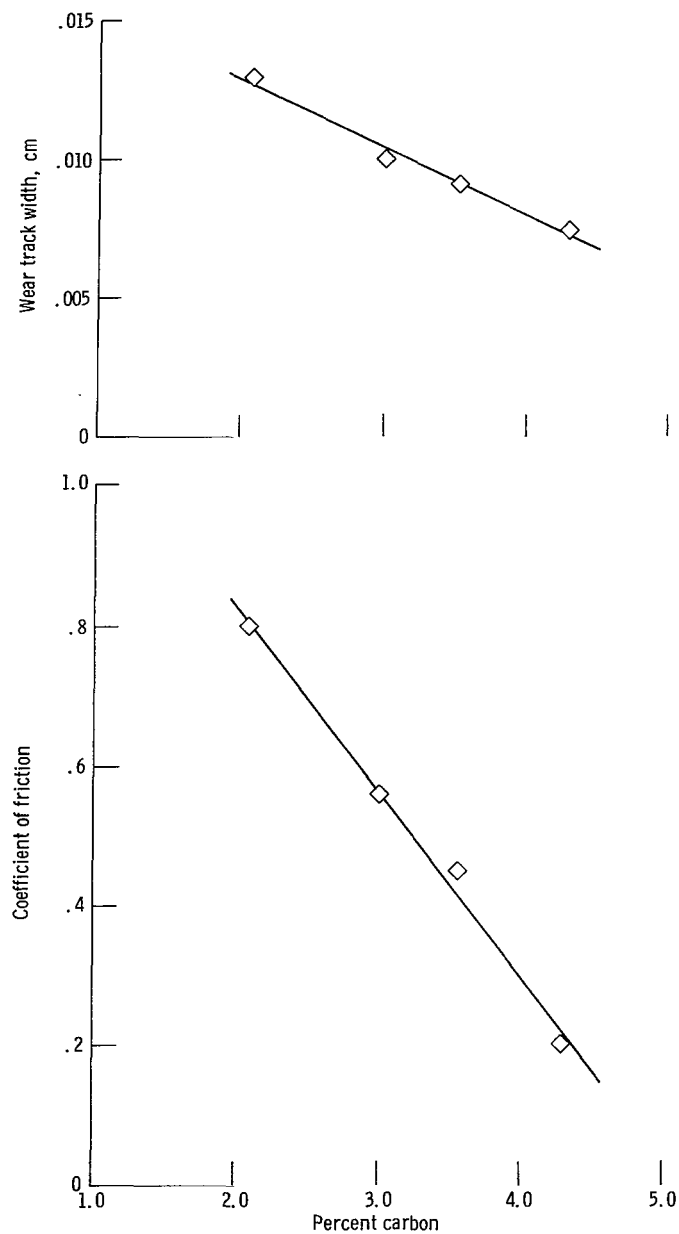


Figure 4. - Coefficient of friction and wear of gray cast iron as a function of carbon content. Mating surface steel ball, 2.5 millimeter diameter; sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.

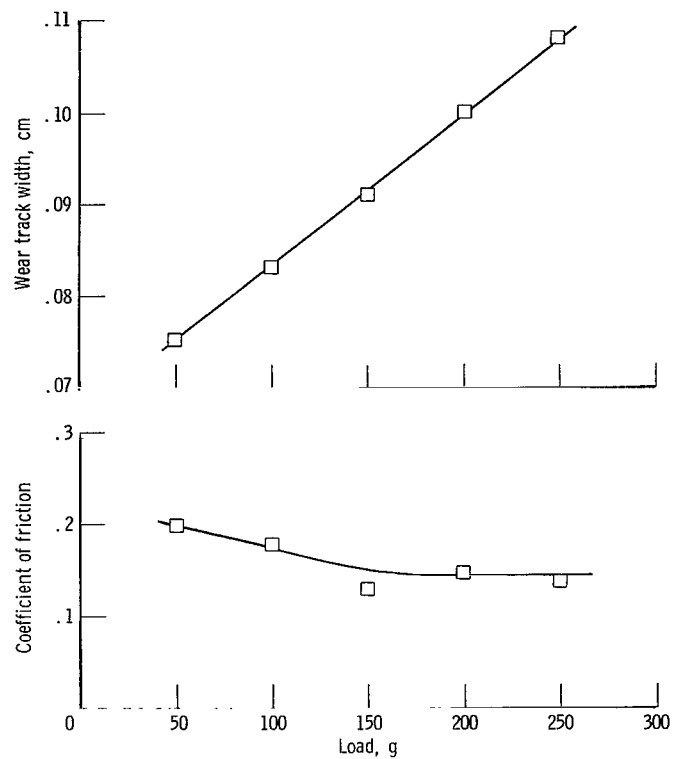


Figure 5. - Coefficient of friction and wear for 4.32 percent carbon containing gray cast iron at various loads. Mating surface steel ball, 25 millimeter diameter; sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.



Figure 6. - Wear track on 3.02 percent carbon in gray cast iron after having been in sliding contact with a 52100 steel ball for 1 hour. Sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C.

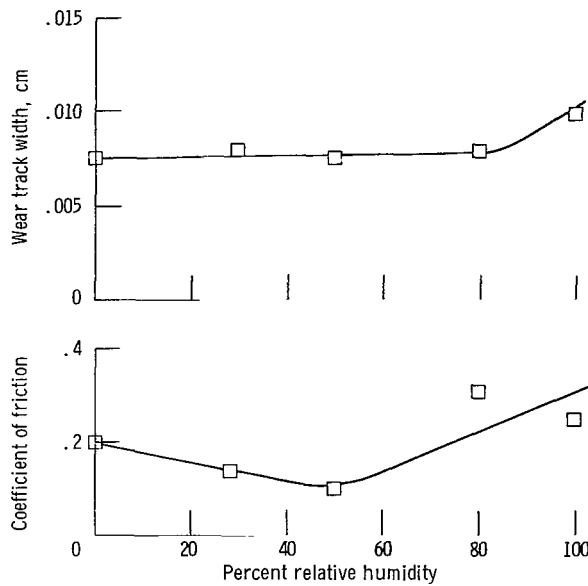


Figure 7. - Coefficient of friction and wear of gray cast iron containing 4.32 percent carbon at various percents of relative humidity. Mating surface steel ball, 2.5 millimeter diameter; sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.

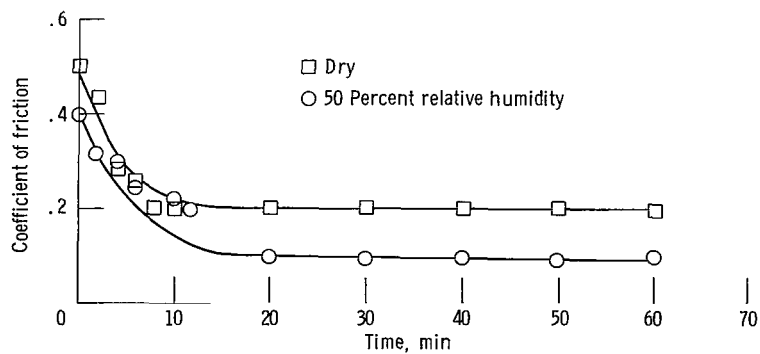


Figure 8. - Coefficient of friction for gray cast iron containing 4.32 percent carbon dry and in an environment containing 50 percent relative humidity. Mating surface steel ball, 2.5 millimeter diameter; sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.



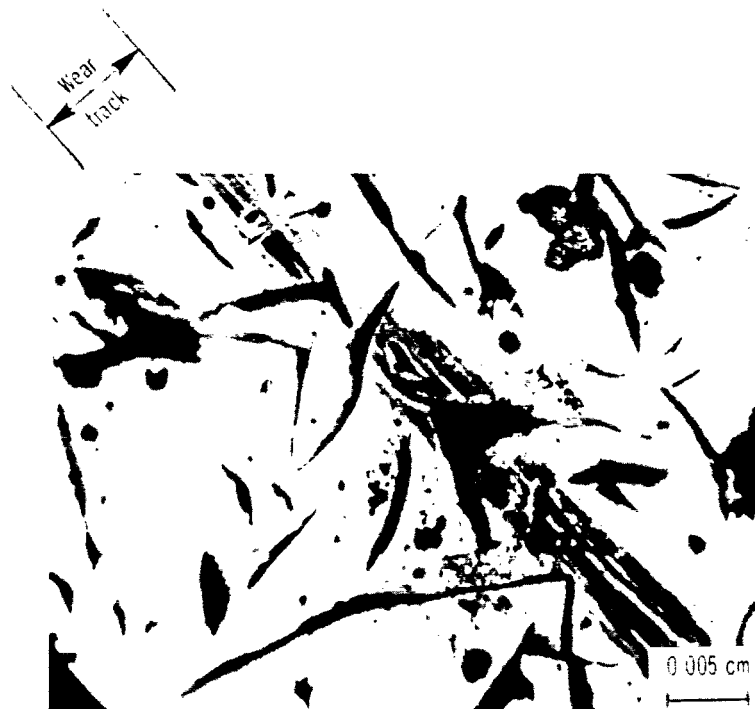
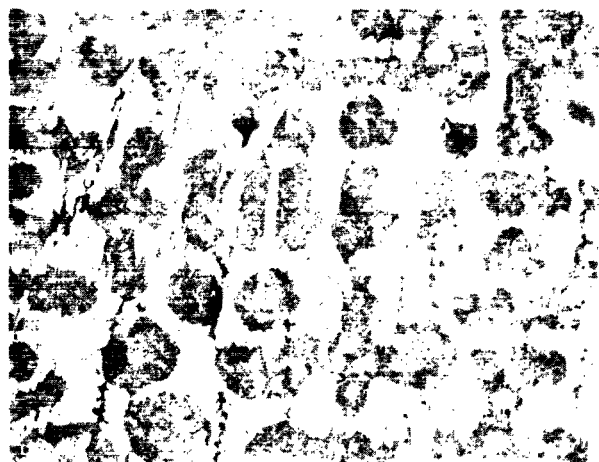


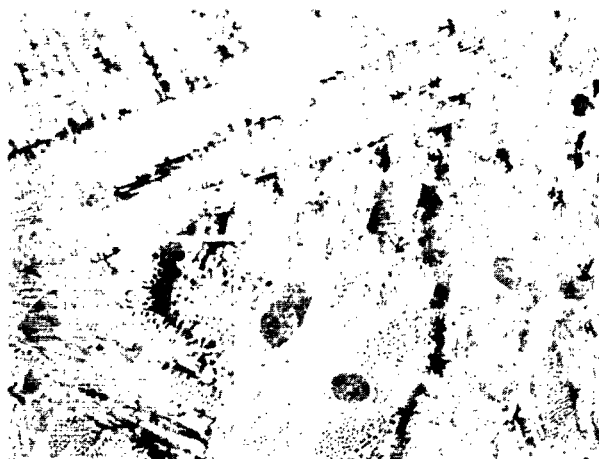
Figure 9. - Wear track on 4.32 percent carbon in gray cast iron after having been in sliding contact with a steel ball and lubricated with a degassed mineral oil. Sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.



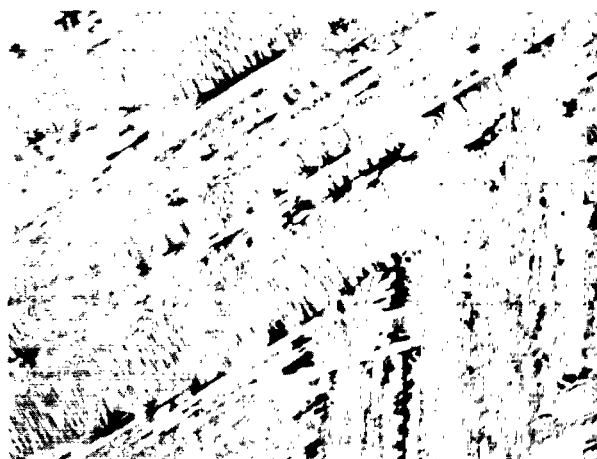
(a) 3.00 percent carbon.



(b) 3.54 percent carbon.



(c) 4.18 percent carbon.



(d) 4.32 percent carbon.

Figure 10. - Photomicrographs of white cast iron.

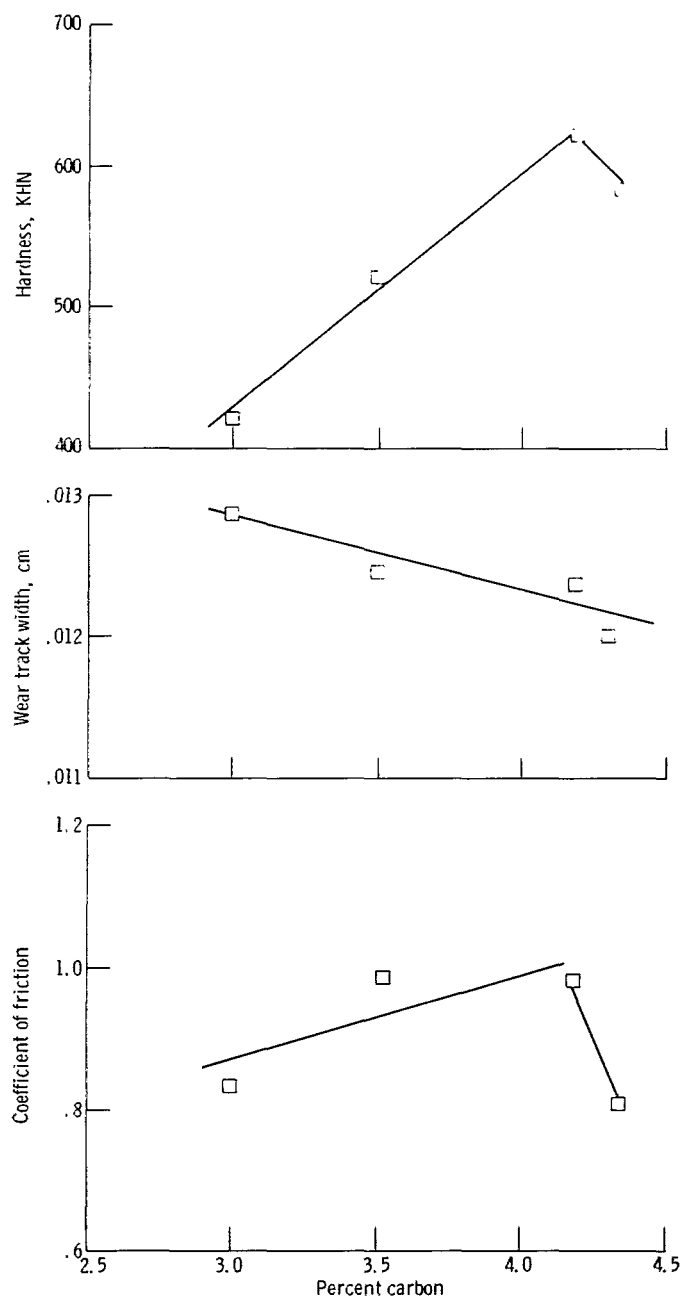


Figure 11. - Coefficient of friction, wear, and hardness of white cast iron as a function of carbon content. Mating surface steel ball, 2.5 millimeter diameter; sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.

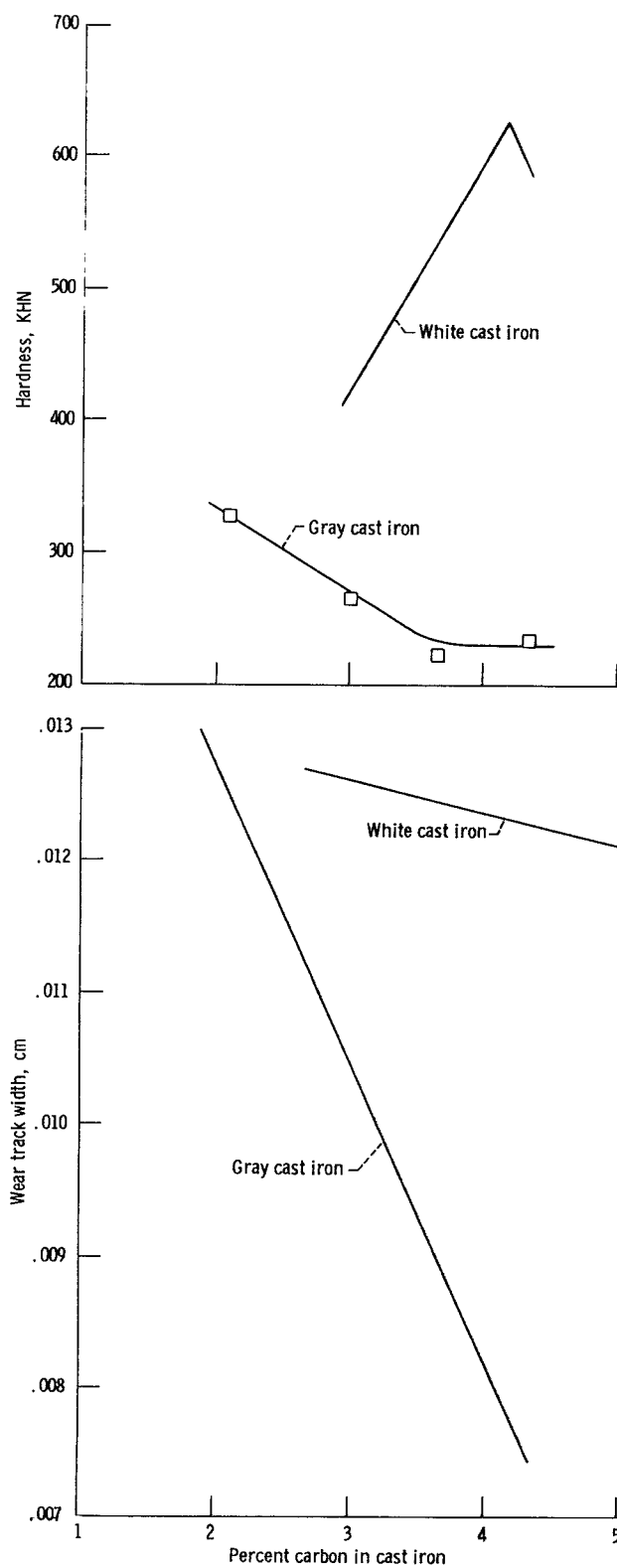


Figure 12. - Comparison of hardness and wear for white and gray cast irons.

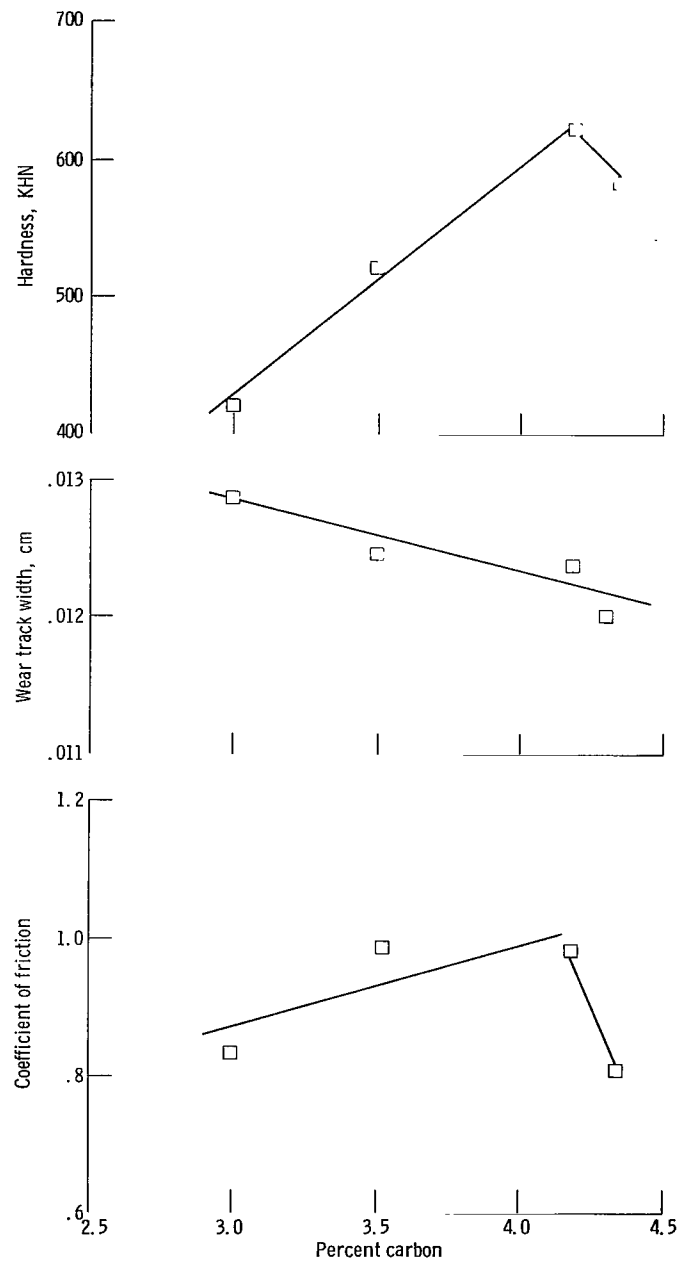


Figure 11. - Coefficient of friction, wear, and hardness of white cast iron as a function of carbon content. Mating surface steel ball, 2.5 millimeter diameter; sliding velocity, 5 centimeters per minute; load, 50 grams; argon atmosphere; temperature, 23° C; duration, 1 hour.

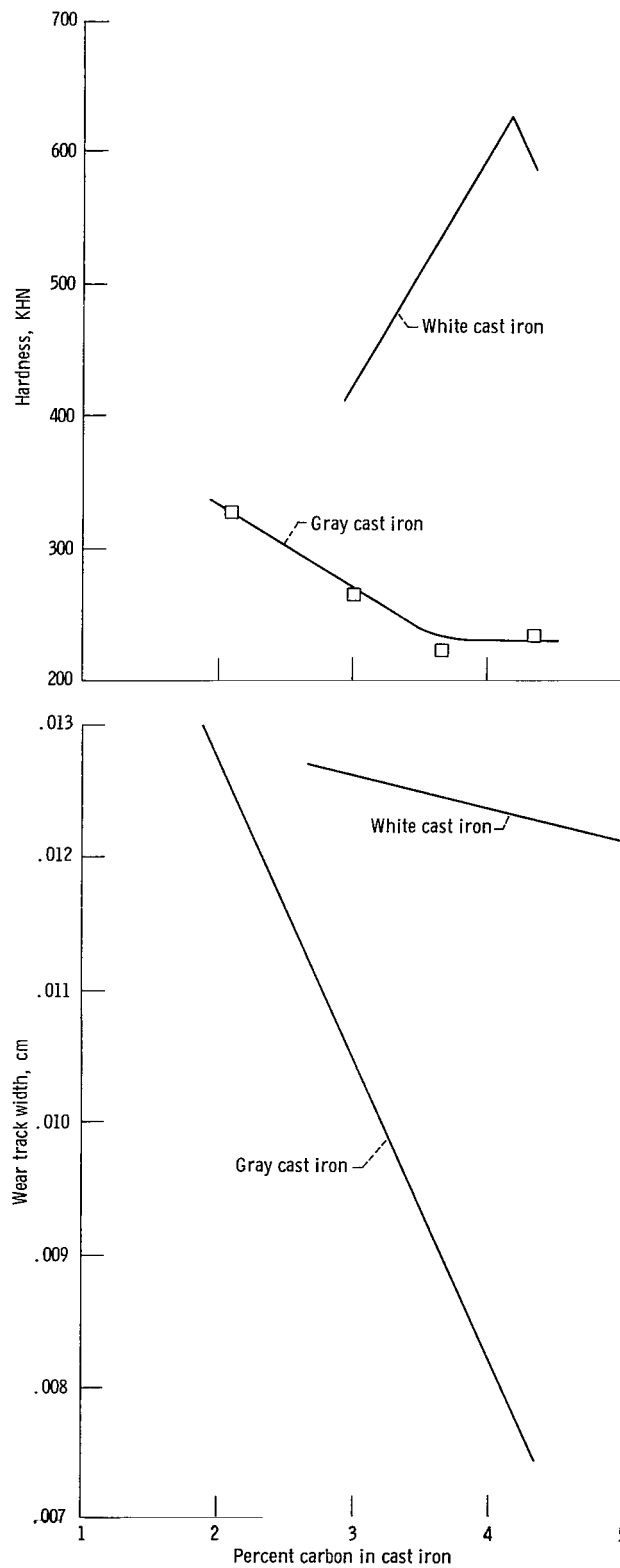


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1. Report No. NASA TP-1052		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle <b>EFFECT OF CARBON CONTENT ON FRICTION AND WEAR OF CAST IRONS</b>				5. Report Date September 1977	
				6. Performing Organization Code	
7. Author(s) Donald H. Buckley				8. Performing Organization Report No. E-9110	
				10. Work Unit No. 506-16	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Paper	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract Friction and wear experiments were conducted with cast irons and wrought steels containing various amounts of carbon in the alloy structure in contact with 52100 steel. Gray cast irons were found to exhibit lower friction and wear characteristics than white cast irons. Further, gray cast iron wear was more sensitive to carbon content than was white. Wear with gray cast iron was linearly related to load and friction was found to be sensitive to relative humidity and carbon content. The form in which the carbon is present in the alloy is more important as the carbon content and no strong relationship seems to exist between hardness of these ferrous alloys and wear.					
17. Key Words (Suggested by Author(s)) Friction Wear Cast iron Carbon in iron			18. Distribution Statement Unclassified - unlimited STAR Category 26		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		22. Price* A02	
				21. No. of Pages 20	

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